Chapter 2
Site Characterization

2-1. Site Characterization Requirements

Planning, design, and execution of a beach fill project require the collection of a large amount of data on the project area and surroundings. These project area characteristics must then be incorporated into formulation and design studies. This will form the basis for project design and should contain all the information necessary for design purposes. Some of the information required includes a description of the important geomorphological characteristics of the area, sediment characteristics of the project beach and potential borrow areas, hydrodynamics and coastal processes of the site, and existing conditions of the project site, including extent and rate of erosion, and existing shore protection structures. Some of the needed data and information on the project area will probably be available in existing publications, maps, charts, and aerial photography; however, a field data collection effort will normally be required to supplement the available data.

2-2. Geomorphology

Many beach, dune, and nearshore characteristics are related to regional and local geomorphic patterns and processes. A study of these factors is an important part of the design process so that the important elements which influence the behavior of the beach fill are understood. Regional geomorphic information can usually be obtained by analyses of maps, charts, and literature sources. In most cases, much of the information needed to adequately describe the local geomorphology, including the project area, must be based on field reconnaissance and survey. Knowledge of longshore transport and deposition of sediment is important in the design of nourishment projects. Along coasts with complex circulation and sediment transport, the use of relatively simple techniques utilizing morphological information can be employed to interpret such information. The relative magnitude and variability of these parameters can also be determined via morphological indicators.

a. Regional geomorphology. Information on the regional geomorphic setting of a project site gives insight into the nature and evolution of the shore zone, sediment supply, hydrodynamic environment, and location of borrow sources. For example, the long straight dune-backed barrier islands and spits typical of coastal plains are quite different from the comparatively short beaches flanked by headlands frequently encountered in hilly or mountainous terrain. Sediment supply on coastal plain shores is likely to be dominated by littoral drift processes and onshore-offshore movement while little sand is contributed by streams because their lower courses are drowned. In contrast, beaches in hilly or mountainous regions are most often supplied by erosion of nearby headlands and cliffs and by sediment-laden streams. An example of using regional morphology in the determination of littoral transport direction is presented in Figure 2-1. The southern California coast is broken into several cells based on the location of inlets, offshore bathymetry, and wave refraction patterns, which have a large influence on the direction of longshore sediment transport within the region. These differences are extremely important when analyzing sediment budgets for a project (see EM 1110-2-1502).

(1) Regional scale geomorphology of the continental shelf is important because of its influence on wave dynamics, and because it is often a source or sink of littoral sediment. Furthermore, the continental shelf often contains deposits of suitable beach fill material. Continental shelf morphology usually shows a similarity to the morphology of the adjacent land mass but may have been altered to some degree by marine processes. Shelves bordering coastal plain regions are likely to be wide, gently sloping platforms having a relatively low relief. They often contain shoals composed of unconsolidated sand-size material that are potentially useful for beach fill. Shelves bordering hilly or mountainous coasts tend to be comparatively narrow, more steeply sloping, and have an irregular relief.

(2) Regional terrestrial geomorphology site characterization studies should include descriptions of landform relief and configuration, drainage patterns, and coastal features. This information can be obtained from pertinent texts and journal papers giving descriptions of specific regions, and by analysis of topographic maps and small-scale aerial photographs. The regional geomorphology of continental shelves is less well known than for terrestrial areas. The main basic source of information is the bathymetric charts produced by the National Ocean Survey of the National Oceanographic and Atmospheric Agency. Sand deposits can be identified by the Minerals Management Service of the Department of the Interior.

b. Project site morphology. A consideration of project beach morphology should include a detailed survey of the dune, beach, and nearshore areas from the dunes, cliff, or other features (e.g. shore protection structures) backing the beach to an offshore depth that will encompass the approximate zone of significant sediment movement. Figure 2-2 illustrates and defines the beach morphology that is typical of most project beaches. Customarily, morphology is delineated by survey of data points along shore-perpendicular profile lines referenced to a shore-parallel baseline that is, in turn, referenced to the state survey

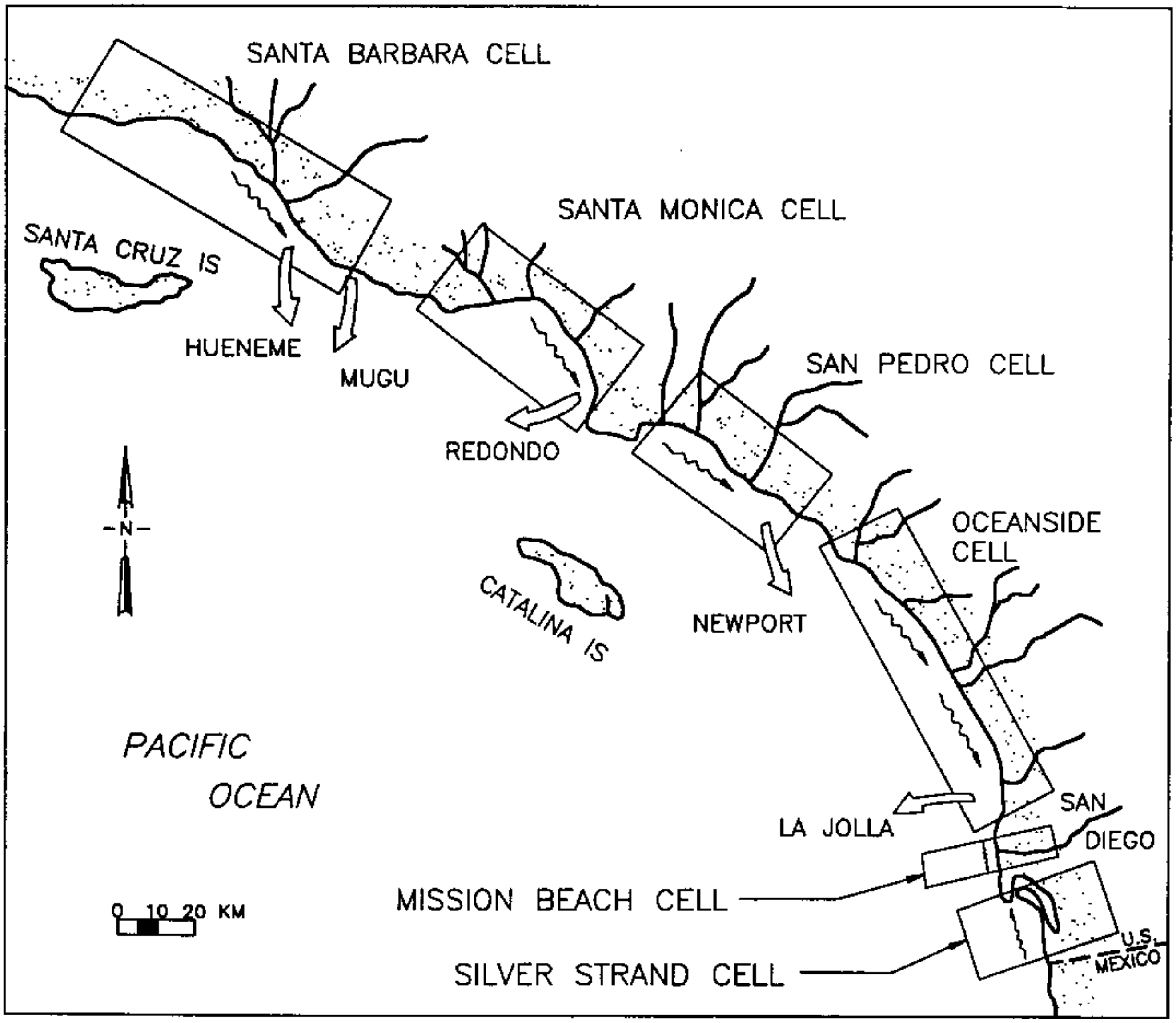

Figure 2-1. Regional coastal features along the southern California coast showing littoral cells based on morphological structures

coordinate systems, or Corps of Engineers benchmark or monuments (see EM 1110-2-1003). Natural and artificial morphological features of a project site may influence local processes, revealing valuable information about that area. For example, examination of structural features may reveal the direction of longshore sediment transport for a project area (Figure 2-3). Information of this nature would be valuable in design considerations for a beach fill project. Also, aerial photographs can be converted to shoreline position maps for use in compiling sediment budgets, assessing long-term shoreline recession rates, and assessing other historical changes (see EM 1110-1-1000).

(1) The most important features of the profile lines are their length and spacing. On dune-backed beaches, profile lines should extend inland across the primary dune. Where cliffs or structures back the beach, profiles should originate far enough behind their base to ensure the baseline is not lost to future erosion. Profiles should extend offshore far enough to encompass the active profile or depth of closure. Defining depth of closure is a controversial issue in the field of coastal engineering and this term is often misinterpreted and misused. This boundary has been approximated by analysis of wave statistics (Hallermeier 1977, 1978, and 1981) or repetitive profiles carried out over a sufficient period of time to show profile adjustments to a wide range of hydrodynamic conditions to the seaward extent of sediment movement. For engineering practices, depth of closure is commonly defined as the minimum water depth at which no measurable or significant change in bottom

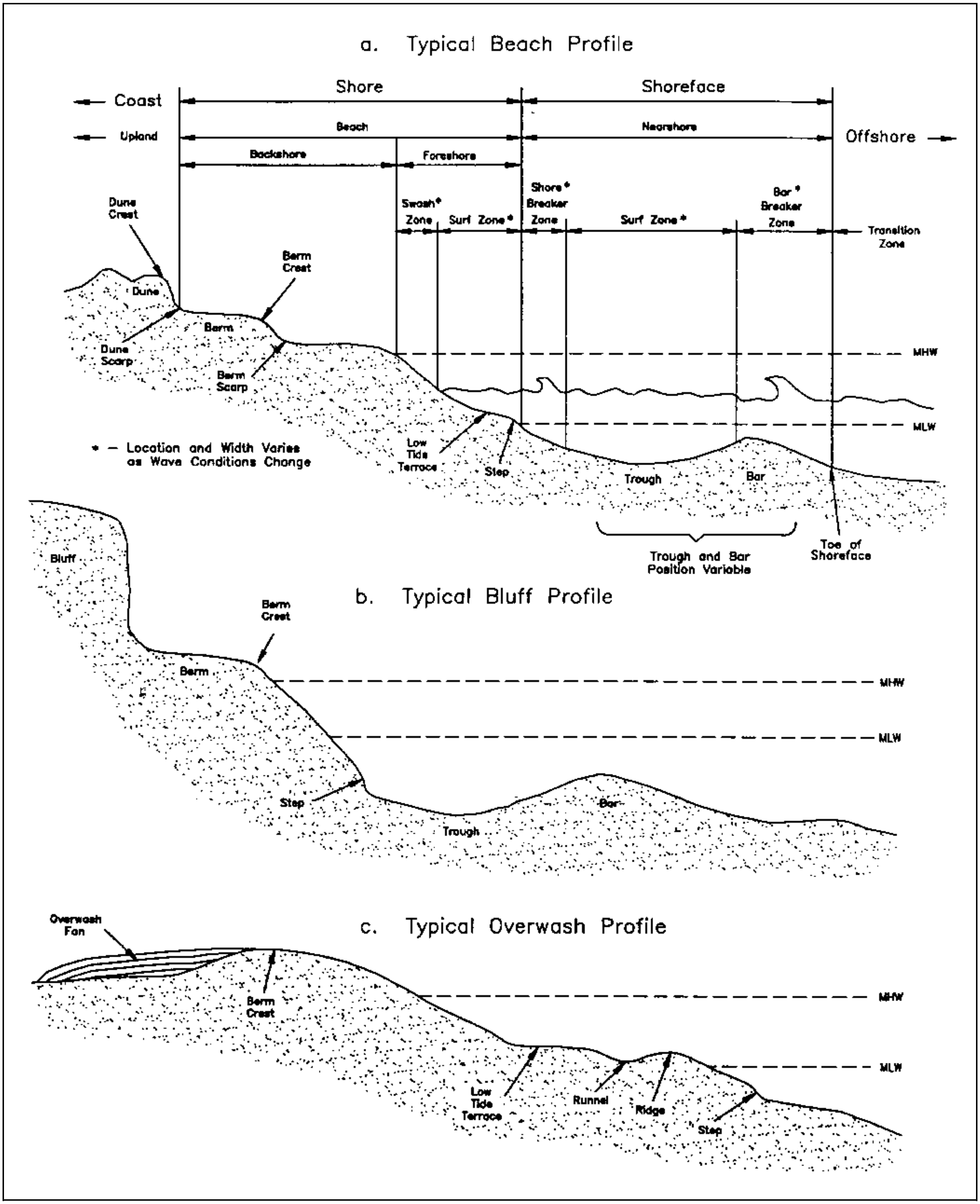

Figure 2-2. Beach morphology for most typical project beaches

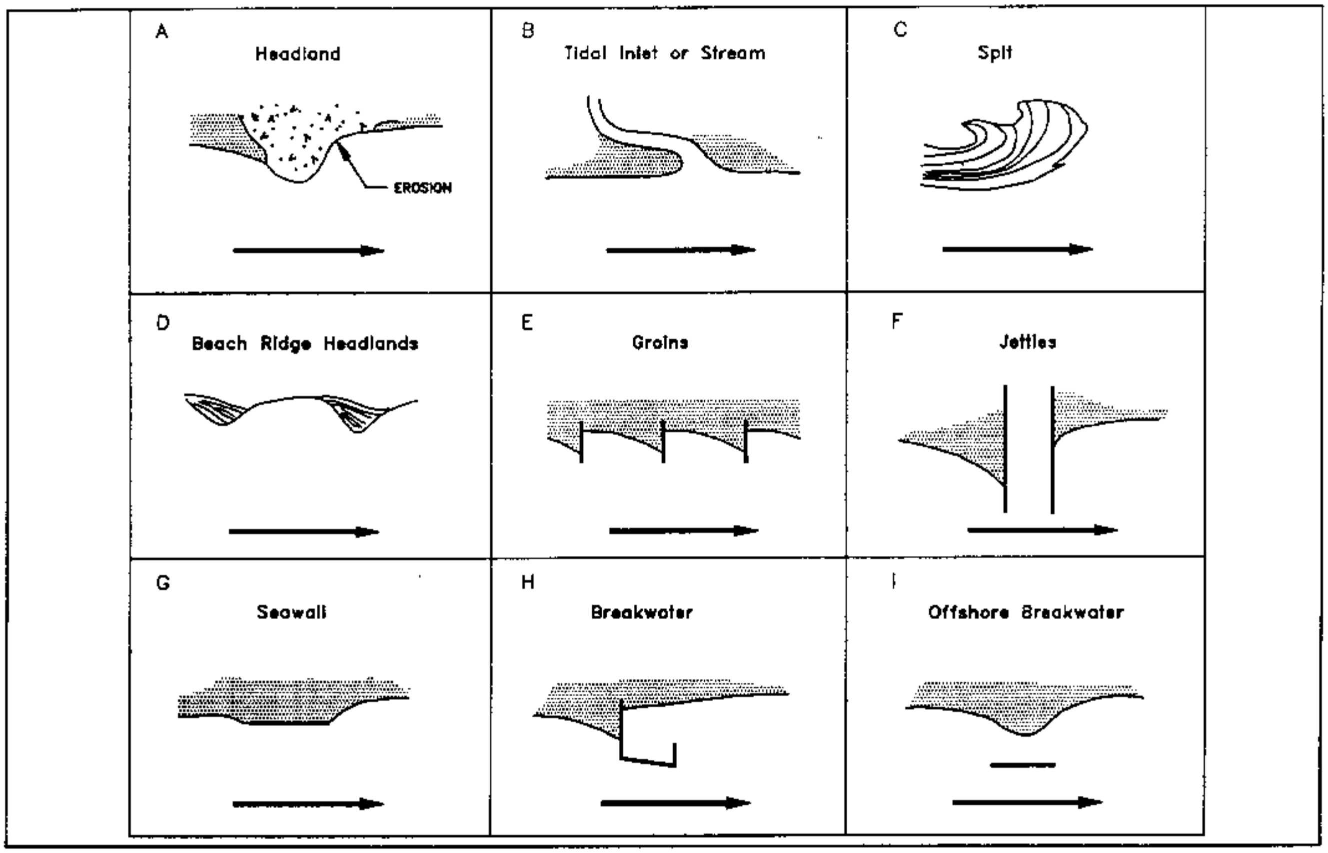

Figure 2-3. Various local coastal morphological features that can be used as indicators of littoral drift direction

depth occurs (Stauble et al. 1993). This definition allows for considerable variations in depth of closure interpretation. Factors such as tidal currents, sand size, and bottom slope play a role in defining the limit depth of the active profile; however, wave height and period have long been recognized as the dominant factors in beach processes (Hallermeier 1977).

(2) Using laboratory tests and limited field data from the Pacific Ocean and Gulf of Mexico, Hallermeier (1977, 1978, and 1981) developed approaches for predicting the limits of extreme wave-related sediment transport. Birkemeier (1985) used extensive field data for the Altantic Ocean, collected at CERC's Field Research Facility in North Carolina, to modify the relationship developed by Hallermeier. These methods assume a non-breaking significant wave height that is exceeded 12 hr/year (0.137 percent of the time). Both methods can be simplified to relate the depth of closure to the mean annual significant wave height and represented as:

$$H = 1.5\ H_{S_{0.137}} = 6.75\ H_S \tag{2-1}$$

where

H = annual depth of closure (m)
H_S = mean annual significant wave height (m)

For example, if the mean annual wave height (H_S) for a specific area is 1.5 m (4.9 ft), the annual depth of closure would be 10.1 m (33.1 ft).

(3) When surveys covering several years are available for a project site, closure is best determined by plotting and analyzing the profiles. The closure depth computed in this manner reflects the influence of storms as well as of calmer conditions. Kraus and Harikai (1983) evaluated the depth of closure as the minimum depth where the standard deviation in depth change decreased markedly to a near-constant value. Using this procedure, they interpreted the landward region where the standard deviation increased to be the active profile where the seafloor was influenced by gravity waves and storm-driven water level changes. The offshore region of smaller and nearly constant standard deviation was primarily influenced by lower frequency sediment-transporting processes such as shelf and oceanic currents (Stauble et al. 1993). It must be noted that the smaller standard deviation values fall within the limit of

measurement accuracy. This suggests that it is not possible to specify a closure depth unambiguously because of operational limits of present offshore profiling hardware and procedures.

(a) An example of how closure was determined empirically at Ocean City, MD, is shown in Figure 2-4. A clear reduction in standard deviation occurs at a depth of about 5 to 7 m (18 to 20 ft). Above the ~6-m (~18-ft) depth, the profile exhibits large variability, indicating active wave erosion, deposition, and littoral transport. Deeper (and seaward) of this zone, the lower and relatively constant deviation of about 7 to 10 cm (3 to 4 in.) is within the measurement error of the sled surveys. Nevertheless, despite the inability to precisely measure seafloor changes in this offshore region, it is apparent that less energetic erosion and sedimentation take place here than in water shallower than ~6 m (~18 ft). For the 5.6 km (3.5 miles) of shore surveyed at Ocean City, the depth of closure ranged between 5 and 8 m (18 and 25 ft). Scatter plots indicated that the average closure depth was 6 m (20 ft).

(4) In many studies on the east coast of the United States, profiles have been extended offshore to the 9-m (30-ft) depth contour. This is based on a generally held view that sediment movement of beach fill engineering significance generally takes place in water depths less than this. On the exposed west coast of the United States this limit is deeper, while for Great Lakes and Gulf of Mexico beaches the depth of significant sediment movement has been reported to be approximately 6 m (20 ft) (*Shore Protection Manual* 1984). CERC TP-78-4 (Everts 1978) is a study of shoreface and continental shelf geometry, which suggests that the transition zone between the shoreface and ramp (i.e., the relatively gentler sloping shelf floor) is possibly related to a long-term depth limit of significant sediment movement. In a series of 49 profiles from the Atlantic and Gulf regions, a large majority had a shoreface/ramp transition depth of more than 9 m (30 ft). In general, the most conservative depth limit for nearshore profiles would be the shoreface/ramp transition depth. Determination of the depth and distance from shore to the shoreface/ramp boundary requires detecting the often subtle grade change from one slope to another. An approximation can be obtained by examination of profiles on which the ramp slope is projected under the shoreface and selecting the point of divergence between the two.

(5) Horizontal spacing of profile lines depends largely on the variability of the beach and nearshore morphology. The degree of variability can be established by reconnaissance and analysis of available maps, hydrographic charts, and aerial photographs. The spacing need not be the same throughout the project area; closer than average spacing may be needed on more complex sections. Profile spacing on long uniform beaches often ranges from 300 to 600 m (1,000 to 2,000 ft). Stauble et al. (1993) (Figure 2-5) describe alongshore variability in seaward distance of active profiles relative to shoreface-attached shoals at the beach fill site in Ocean City, MD. In general, the spacing of profile lines should be close enough so that major beach features such as nearshore shoals, major cusps, spits, headlands, fillets around structures, and profile changes can be delineated by the survey data.

(6) Subaerial parts of the profile are usually surveyed by transit, rod and tape, or electronic ranging devices using standard survey techniques. Enough data points along each profile are needed to clearly show the beach morphology, often at 6-m (20-ft) intervals and at all changes in beach slopes or elevations. The submerged parts of the profiles can be surveyed by any of several methods. One consists of a vessel equipped with a fathometer and a positioning system to establish horizontal control. A second, more accurate method, makes use of a sea sled on which is mounted a stadia rod or electronic distance measuring device reflector mirror on a tall mast. The sled is towed along the bottom by a boat or an amphibious vehicle following the profile line, while elevations and horizontal position are determined by a surveying instrument located on shore. The sea sled method has the advantage of being more accurate in establishing elevations because it is independent of the sea state and tidal or other variations in water level. In addition, sea sleds are particularly useful close inshore where a survey vessel cannot safely venture and where fathometer records tend to deteriorate. In many cases, a combination of sea sled inshore and fathometer survey offshore can be advantageously used, especially where profile lines are quite long and extend to relatively deep water. On a smooth bottom, data points are taken at least once for each 30-cm (1-ft) change in bottom elevation. On more irregular bottoms, readings should be taken at a minimum of every 6 m (20 ft).

(7) Beach morphology tends to vary seasonally and substantial differences may occur between winter and summer profiles. In addition, longer term changes can occur as a result of shoreline erosion, major storm events, or interruption of sediment supply. Although long-term profile data are preferred, analysis of historical aerial photographs and bathymetric charts can provide valuable information on long-term changes. It is necessary to obtain at least one set of profiles for both winter and summer conditions for use in design. Figure 2-6 presents a scenario of beach profile responding to storm conditions causing long-term changes. Figure 2-7 shows seasonal beach profile response, illustrating the transformation between summer and winter profile shapes.

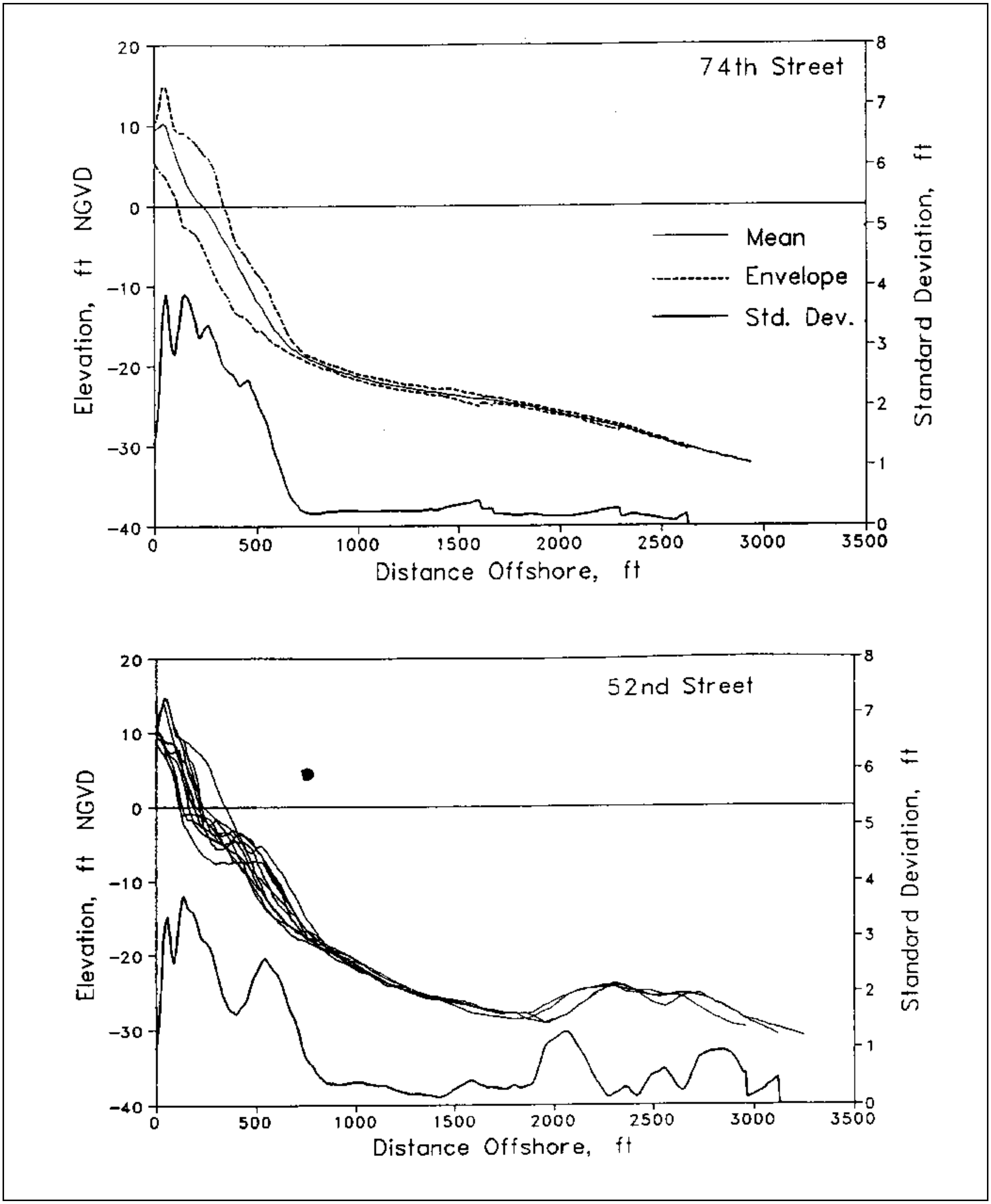

Figure 2-4. Profile surveys from Ocean City, MD, showing the seaward extent of sediment movement or depth of closure (from Stauble (1993))

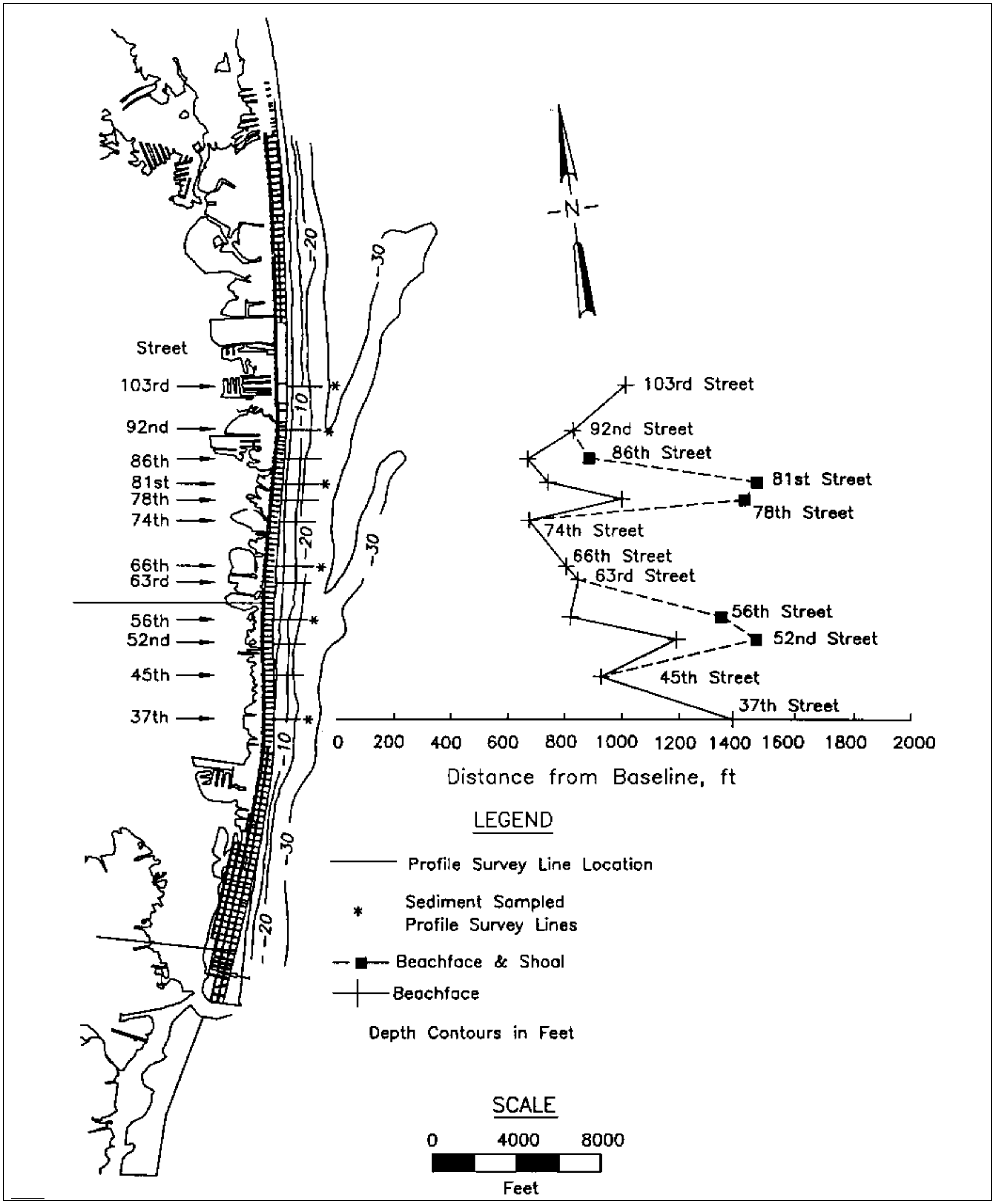

Figure 2-5. Alongshore variability in seaward distance of active profile envelope relative to two shoreface-attached shoals (from Stauble et al. (1993))

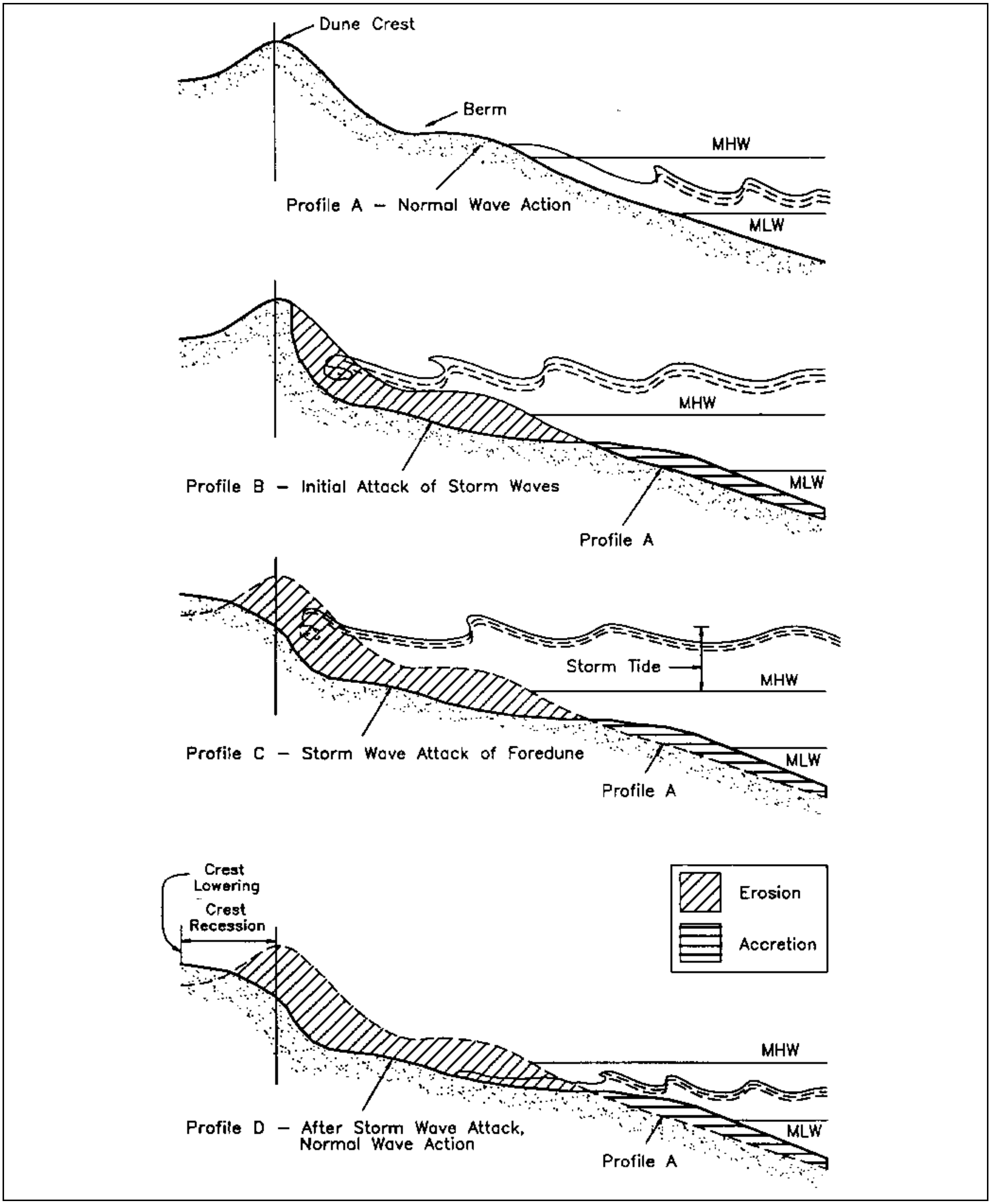

Figure 2-6. Beach response to storm conditions. This type of response typically causes long-term damage to the profile

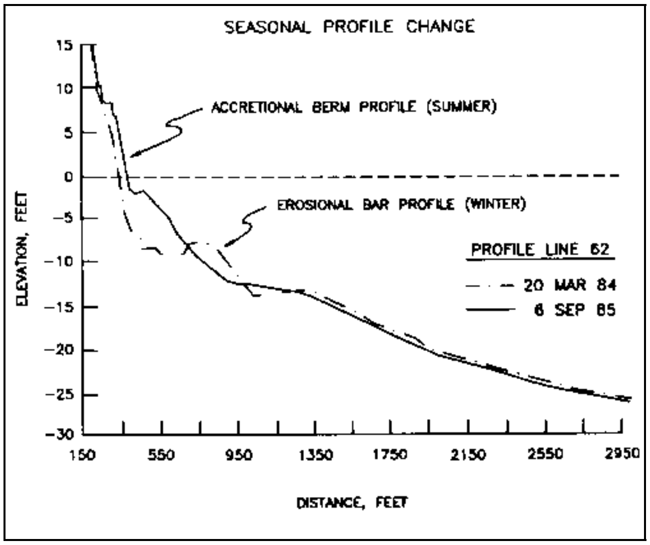

Figure 2-7. Typical seasonal profile variation showing the transition between winter and summer conditions at the Coastal Engineering Research Center's Field Research Facility in Duck, NC

c. Tidal inlets. Inlets are passages between the ocean and bays, estuaries, lagoons, or other bodies of water. Most tidal inlets are located along barrier islands, barrier spits, and baymouth barriers. Because they are located in unconsolidated material, inlets on barrier coasts tend to be unstable unless they are flanked by jetties. Inlets have a substantial effect on beach development, both locally and on beaches several miles away. Episodes of erosion and accretion revealed by historical shoreline change are often related to the opening and closing or natural sand bypassing episodes of inlets. Influence on distant beaches is due to the fact that inlets often create a partial or total interruption of sediment moving alongshore, thus causing deficiencies of sediment supply in downdrift areas as illustrated in Figure 2-8. Most of this sediment is either impounded in jetty fillets, or in ebb and flood tidal shoals (on ocean coasts) that form seaward and landward of the inlet, respectively. Some material may be transported by tidal currents to offshore or back-barrier areas where it is effectively removed from the longshore transport system. A more localized effect of inlets is through the formation of ebb tidal shoals, which affect the energy and direction of waves approaching the shore through refraction. In some cases the refraction effects may locally reverse the longshore current direction on the downdrift shoreline. Further detailed guidance on inlet analysis is provided in EM 1110-2-1618.

d. Adjacent coastal areas. It is important that beach profile measurements be taken beyond the lateral boundaries of the project area to establish baseline behavior of adjacent

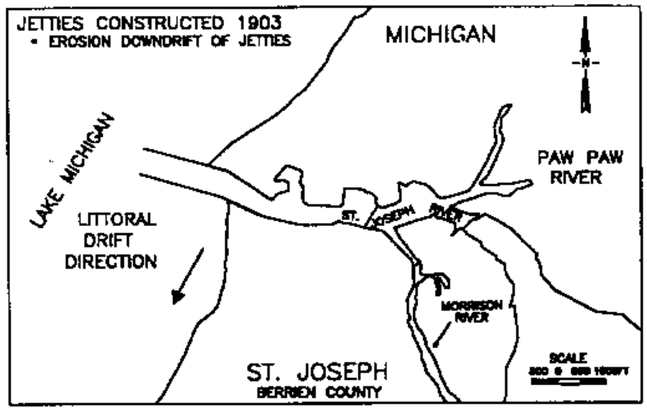

Figure 2-8. Jetties in Lake Michigan interrupting longshore transport. Accretion on the north side indicates a net southerly littoral transport (from Parson (1992))

beaches. These profiles are used both for design of beach fill termination, and for post-project monitoring. Therefore, the profiles must be surveyed during the pre-project study in order to provide control data in the updrift and downdrift locations. In post-project monitoring, the profiles have the following two purposes: (1) comparison of the response of the filled beach to a more natural beach under essentially the same environmental conditions, and (2) detection of any lateral movement of material out of the project area by changes in profile volume, or appearance of natural tracers associated with the fill material.

2-3. Historical Shoreline Change

Information on the historical change of a project beach is an important factor in specifying initial and periodic nourishment fill requirements and projecting future change. Items of principal interest are historical changes in shoreline position, existence, and characteristics of relict inlets, and variations in the character and position of dunes, cliffs, or other features backing the beach. In large part, long-term historical data are obtained from maps, charts, aerial photographs, and descriptive records. The available information varies considerably from place to place and in the periods of time covered.

a. Shoreline trends. One of the most important historical items of information is changes in shoreline position due to erosion and accretion. Shoreline movements due to erosion or accretion usually represent a net change in the volume of beach material. In some areas, shorelines move consistently landward or seaward over long periods of time, while in other areas shorelines may alternate between landward and seaward movement, or remain more or less stable in one position. These changes may occur seasonally;

however, it is important to know an area's storm history relative to shoreline position data such as aerial photos and surveys.

(1) The principal method of analyzing shoreline and volume change through time is by compiling shoreline and bathymetric change maps. These are large-scale maps containing superimposed shorelines and depth contours for each of the historical surveys available. From these maps, measurements can be made of the difference in contour line position between any two survey dates. These measurements can be used to compute annual change rates for specific periods of time. Figure 2-9 presents an example of a shoreline and bathymetric change map compiled for Tybee Island, Georgia (Oertel, Fowler, and Pope 1985). Data for maps are usually obtained from topographic and bathymetric maps produced by the National Ocean Survey (NOS) of the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), and from aerial photography. In many cases, the published maps and charts are too small in scale to accurately indicate shoreline changes; however, larger scale plots used in the original compilation of the published charts are usually available from the mapping agency files. Both NOAA and the USGS are good sources of aerial photographs. For purposes of analyzing shoreline changes, the largest scale photography available should be used. Care should be taken to compare shorelines surveyed during the same time of year to remove seasonal change bias from the analysis.

(2) There are a number of computer-based techniques available which can improve the accuracy of shoreline change mapping, and reduce the need for manual data plotting and measurement. These include computer digitizers to enter the data into a common database and scale; Geographic Information Systems to archive historical data and perform data manipulation; civil engineering volume calculation programs for calculating historical volume changes, and custom computer programs.

(3) Differences in the degree of accuracy in the original survey and compilation techniques of source maps may create a margin of error large enough to account for small differences in shoreline position between given dates. This is especially true of older sources that were based on survey instruments and techniques less precise than those of modern times. For this reason, small changes in shoreline position should be carefully evaluated as to their validity.

(4) Shoreline change maps of many areas of the United States coasts have been made in the past by Government agencies and can be updated to include more recent survey data. These maps are usually available in Corps District and Division files. In a recent cooperative program between CERC and NOAA, shoreline change maps have been compiled on two regions of the Atlantic Coast. The first covers the Atlantic Coast from Cape Henry, Virginia, to Cape Hatteras, North Carolina (Everts, Battley, and Gibson 1983) and the second extends between Tybee Island, Georgia, and Cape Fear, North Carolina (Anders, Reed, and Meisburger 1990).

c. Dune accretion and erosion. Coastal dunes are an important element in beach fill design, because of their role in protecting inland areas from storm flooding and wave attack. Where they are not well-stabilized, dunes are mobile features continuously being reshaped by winds and periodically being eroded by storm waves. Historical trends in dune accretion, erosion, and displacement are important factors in determining the expected effects of dune filling and stabilization for flood protection. Historical records of dune behavior can be obtained from old topographic maps, photographs, and land use records.

2-4. Sediment Characteristics

A detailed study of the native beach material is a vital element in the design of beach fill projects. Suitability of the fill material selected for the project is based on comparative analysis of the native beach and potential fill material characteristics. This section discusses the methods of collection and analysis of dune, beach, and nearshore samples from the project area. Applicable computer software can be found in the Automated Coastal Engineering System (ACES) Version 1.07 (Leenknecht et al. 1990).

a. Sample collection. An accurate determination of the composition and grain size characteristics of the native dune, beach, and nearshore sediments in the project area is of vital importance in selecting suitable fill material. In order to do this, a sediment sampling program must be devised and carried out. The number and location of samples collected should be such that the samples fully represent the variations in sediment characteristics within the project area. Determination of these factors can best be accomplished by a reconnaissance of the project area using a sediment size comparison chart to estimate the degree and pattern of sediment variability. A suitable size comparison card can be made by gluing sieve fractions of sand on a piece of medium or heavy weight illustration board. During the reconnaissance a small number of representative samples should be secured for laboratory analysis to compare with field estimates and to determine composition.

(1) Normally, sediment samples are collected along the profile lines established to survey site morphology. In most cases, this provides satisfactory results. In some cases, however, it may be necessary to survey additional sampling

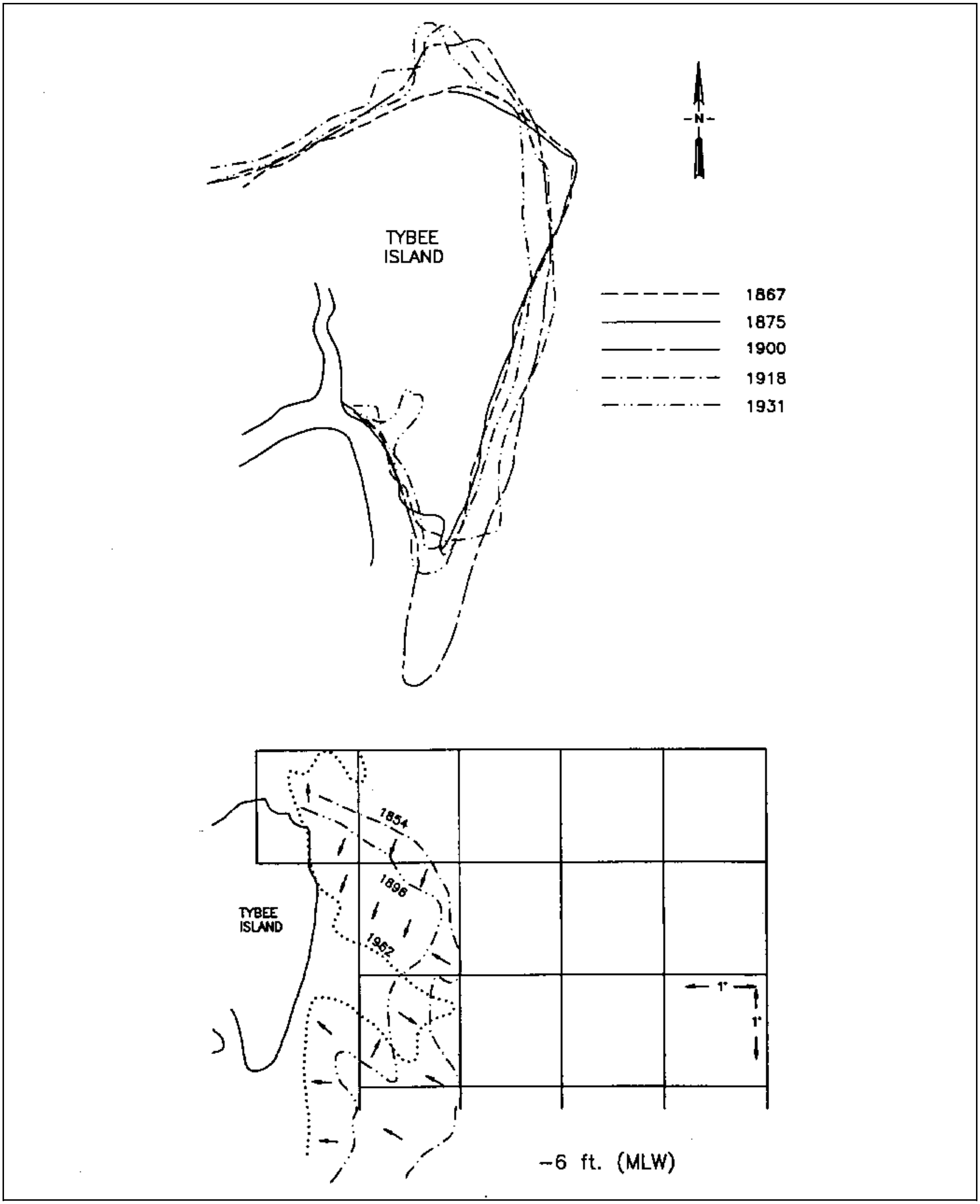

Figure 2-9. Shoreline and bathymetric change maps compiled for Tybee Island, GA

stations between existing profile lines to characterize the sediment distribution pattern. In general, well-sorted sediments, i.e., those having a narrow range of grain sizes, can be characterized by fewer samples than poorly sorted material, i.e., those having a wide range of grain sizes.

(2) Samples obtained for beach fill studies should be taken at prescribed locations along the profile lines. These locations usually correspond to natural shore-parallel zones, specified elevation increments, or tidal data, e.g. mean high water (mhw), mean low water (mlw). Sampling in the hydrodynamic zone (Figure 2-10) usually provides the most useful information: thus samples should include, but are not limited to, the following beach zones:

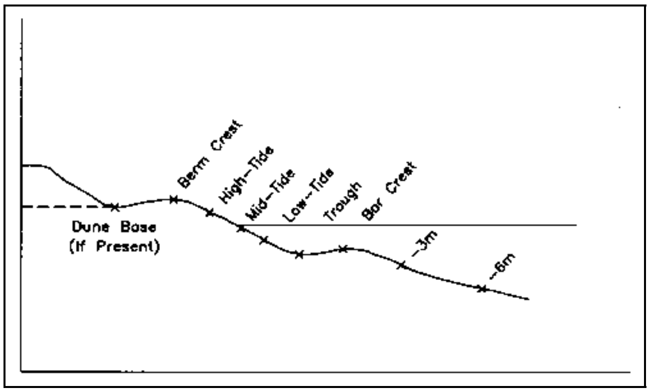

Figure 2-10. Sediment sampling locations across the beach profile based on hydrodynamic zonations

(a) Dune base. Located just seaward of the frontal dune or, in absence of a dune, a seawall, cliff, or vegetation margin marking the inland border of the beach. Samples should be obtained from a 30-cm (12-in.) deep hole to lessen or eliminate aeolian effects.

(b) Mid-backshore. Taken from the backshore zone midway between the berm crest and the dune base or inland border.

(c) Berm crest. At the point of inflection between the normally flat backshore and the steeper foreshore slope. Where no berm is evident, samples are obtained at the approximate high-water line, which is often marked by a line of debris and many times coincides with the upper limits of the swash.

(d) High-tide mark. At the limit of wave uprush as it exists at the time samples are taken. If the beach is visited at the time of high tide, sample should be taken from a mid-swash position.

(e) Mid-tide mark. The location approximately midway between the low-tide line and the high-tide mark.

(f) Low-tide mark. At the limit of wave backrush, which is usually marked by a small declivity in the profile. This feature, known as the step, may not always be evident.

(g) Bar trough. The deepest point between the low-tide mark and the bar crest.

(h) Bar crest. The shoalest point on the bar.

(i) Seaward. At predetermined intervals seaward of the bar crest until the approximate depth of closure is reached.

Samples should be collected at low-water stages when the foreshore samples can be easily obtained at the low-tide mark. The sample stations adopted for a particular project should be consistently used for all project and post-project sampling. If the beach is backed by dunes, samples of the windward and leeward sides and the dune crest should be obtained on each selected profile line. If a cliff backs the beach and the cliff face material appears homogenous, two representative samples are sufficient; if it is stratified, samples of each bed should be obtained.

(3) Since beach deposits commonly vary in depth below the surface, frequent inspection of underlying material to determine the thickness and characteristics of beach deposits and to obtain samples of any subsurface beds extensive enough to affect the composite size distribution of the beach material should be made. Krumbein and James (1974) recommend that at least the uppermost 30 cm (12 in.) should be examined.

(4) Coarse detritus consists of discrete particles 1 cm (0.4 in.) or larger in size. Common types of coarse detrital particles are mollusk shells, rock fragments, clay balls, peat fragments, and various man-made objects. Representative samples of this material should be collected from a few stations for its possible value in sediment source and littoral drift studies.

(5) Bottom sediment samples in the nearshore zone are generally obtained by grab samples, pipe dredges, or short gravity corers. Depending on the uniformity of the bottom sediments, all or only selected profile lines are sampled. Sample intervals along the line should be taken at specific morphologic features (i.e. bar trough, bar crest, etc.) and in the absence of such features at specified depths, for instance at -5, -10, etc. out to the depth of closure. Because the nearshore area cannot be directly observed, the spacing of samples should be flexible so that, as sampling progresses, spacing can be altered if necessary to provide adequate coverage.

b. Grain size determination. The grain size distribution of samples collected for the study can be determined by sieve analysis or by a rapid sediment analyzer. Care should be taken if these two methods are used on the same project, because there are differences between the two techniques. Sieves measure the actual diameter of individual grains; the rapid sediment analyzer measures the fall velocity of particles in water and relates it to the actual diameter of a quartz sphere having the same fall velocity. The diameter determined by the rapid sediment analyzer is an effective hydraulic diameter rather than actual diameter and more nearly represents how grains will respond to flow. In actual practice, the differences between the two methods will probably be less than the uncertainties due to sampling variability. Nonetheless, the same method used for determining native beach characteristics for a nourishment site should be used to analyze the fill material. From the size frequency distribution of samples, the standard statistical measures used in sedimentology, including median, mean, sorting, skewness, and kurtosis, can be computed by the method of moments or derived by the Folk graphic method from a plot of the size distribution data.

c. Sediment composition. The main compositional elements of the sediment samples can be determined by examination of the washed sand size fraction under a binocular microscope. It is helpful if the material is subdivided for examination into the Wentworth size classes for sand-size material (Table 2-1). Most beach, dune, and nearshore sediments are composed predominantly of quartz particles. Accessory components of organically produced (biogenic) calcium carbonate and other minerals are usually present. In some areas, biogenic calcium carbonate is the dominant element. The frequency of occurrence of important sediment components can be estimated by their apparent density when viewed under a microscope, preferably, or by frequency counts. Counts can be made in terms of the number of particles of a given element to total particles or per unit weight of sample. In most cases, the accessory elements are present in such small quantities that a count per total particles is impractical in all but the largest particle sizes.

d. Composite grain size. Selection of a suitable fill sand is based largely on comparison of composite grain-size statistics of the project area with that of potential fill sources. Methods of determining composite grain size distribution have been described in Hobson (1977); Stauble, Hansen, and Blake (1984); Stauble and Hoel (1986); Hansen and Scheffner (1990); and Anders and Hansen (1990). Their accuracy depends on how representative the available samples are of the dune, beach, and nearshore areas. One method uses the percentage of sediment in each size interval for all of the samples which are summed. The total value is divided by the number of samples to obtain an average value. The resulting composite average size distribution can be plotted on probability paper and composite sediment statistics determined graphically. A second method mixes equal weight sub-samples of each sample and the grain size distribution of the composite sample is determined by sieve analysis. Figure 2-11 presents examples of composite distribution curves showing variations in composite grain sizes through time for different zones within the profile. Samples representing all geomorphic zones can also be combined to determine the composite grain size for the entire profile. ACES (Leenknecht et al. 1990) provides computer program capabilities for determining composite grain size analysis.

2-5. Hydrodynamics

A detailed knowledge of hydrodynamic forces acting on a coastal area is important in beach fill design since those forces determine both the ultimate long-term beach configuration during typical conditions and the protective quality of the beach during storm conditions. Every project area exhibits a definable range of water levels, waves, and currents. These hydrodynamic forces have historically affected the project area and will act upon any new material placed along the shoreline. Therefore, statistics of both long-term and storm hydrodynamic forces are important in the design of a beach fill project. This section discusses the hydrodynamic information needed for beach fill design and the reader is referred to more detailed discussions about each aspect in EM 1110-2-1414, EM 1110-2-1412, and EM 1110-2-1502.

a. Waves. Wave characteristics of a given area will affect the following aspects of a beach fill project:

(1) Shape of the beach profile.

(2) Offshore limit of sediment motion (depth of closure).

(3) Degree to which the profile recedes during storms.

(4) Direction and rate of longshore transport.

(5) Effect of structures located in the project area.

(6) Extent of wave runup.

(7) Amount of overtopping.

(8) Forces on structures.

Table 2-1
Sediment Grain Size Classification

ASTM (Unified) Classification[1]	U.S. Std. Sieve[2]	Size in mm	PHI Size	Wentworth Classification[3]
Boulder		4096.	-12.0	
		1024.	-10.0	Boulder
	12 in. (300 mm)	256.	-8.0	
		128.	-7.0	Large Cobble
Cobble		107.64	-6.75	
		90.51	-6.5	Small Cobble
	3 in. (75 mm)	76.11	-6.25	
		64.00	-6.0	
		53.82	-5.75	
		45.26	-5.5	Very Large Pebble
Coarse Gravel		38.05	-5.25	
		32.00	-5.0	
		26.91	-4.75	
		22.63	-4.5	Large Pebble
	3/4 in. (19 mm)	19.03	-4.25	
		16.00	-4.0	
		13.45	-3.75	
		11.31	-3.5	Medium Pebble
Fine Gravel		9.51	-3.25	
	2.5	8.00	-3.0	
	3	6.73	-2.75	
	3.5	5.66	-2.5	Small Pebble
	4	4.76	-2.25	
	5	4.00	-2.0	
Coarse Sand	6	3.36	-1.75	
	7	2.83	-1.5	Granule
	8	2.38	-1.25	
	10	2.00	-1.0	
	12	1.68	-0.75	
	14	1.41	-0.5	Very Coarse Sand
	16	1.19	-0.25	
Medium Sand	18	1.00	0.0	
	20	0.84	0.25	
	25	0.71	0.5	Coarse Sand
	30	0.59	0.75	
	35	0.50	1.0	
	40	0.420	1.25	
	45	0.354	1.5	Medium Sand
	50	0.297	1.75	
	60	0.250	2.0	
	70	0.210	2.25	
Fine Sand	80	0.177	2.5	Fine Sand
	100	0.149	2.75	
	120	0.125	3.0	
	140	0.105	3.25	
	170	0.088	3.5	Very Fine Sand
	200	0.074	3.75	
	230	0.0625	4.0	
Fine-grained Soil:	270	0.0526	4.25	
	325	0.0442	4.5	Coarse Silt
Clay if PI ≥ 4 and plot of PI vs. LL is on or above "A" line*	400	0.0372	4.75	
		0.0312	5.0	
Silt if PI < 4 and plot of PI vs. LL is below "A" line*		0.0156	6.0	Medium Silt
		0.0078	7.0	Fine Silt
		0.0039	8.0	Very Fine Silt
*and the presence of organic matter does not influence LL.		0.00195	9.0	Coarse Clay
		0.00098	10.0	Medium Clay
PI = plasticity limit		0.00049	11.0	Fine Clay
LL = liquid limit		0.00024	12.0	
		0.00012	13.0	
		0.000061	14.0	

1. ASTM Standard D 2487-92. This is the ASTM version of the Unified Soil Classification System. Both systems are similar (from ASTM (1993)).
2. Note that British Standard, French, and German DIN mesh sizes and classifications are different.
3. Wentworth sizes (in inches) cited in Krumbein and Sloss (1963).

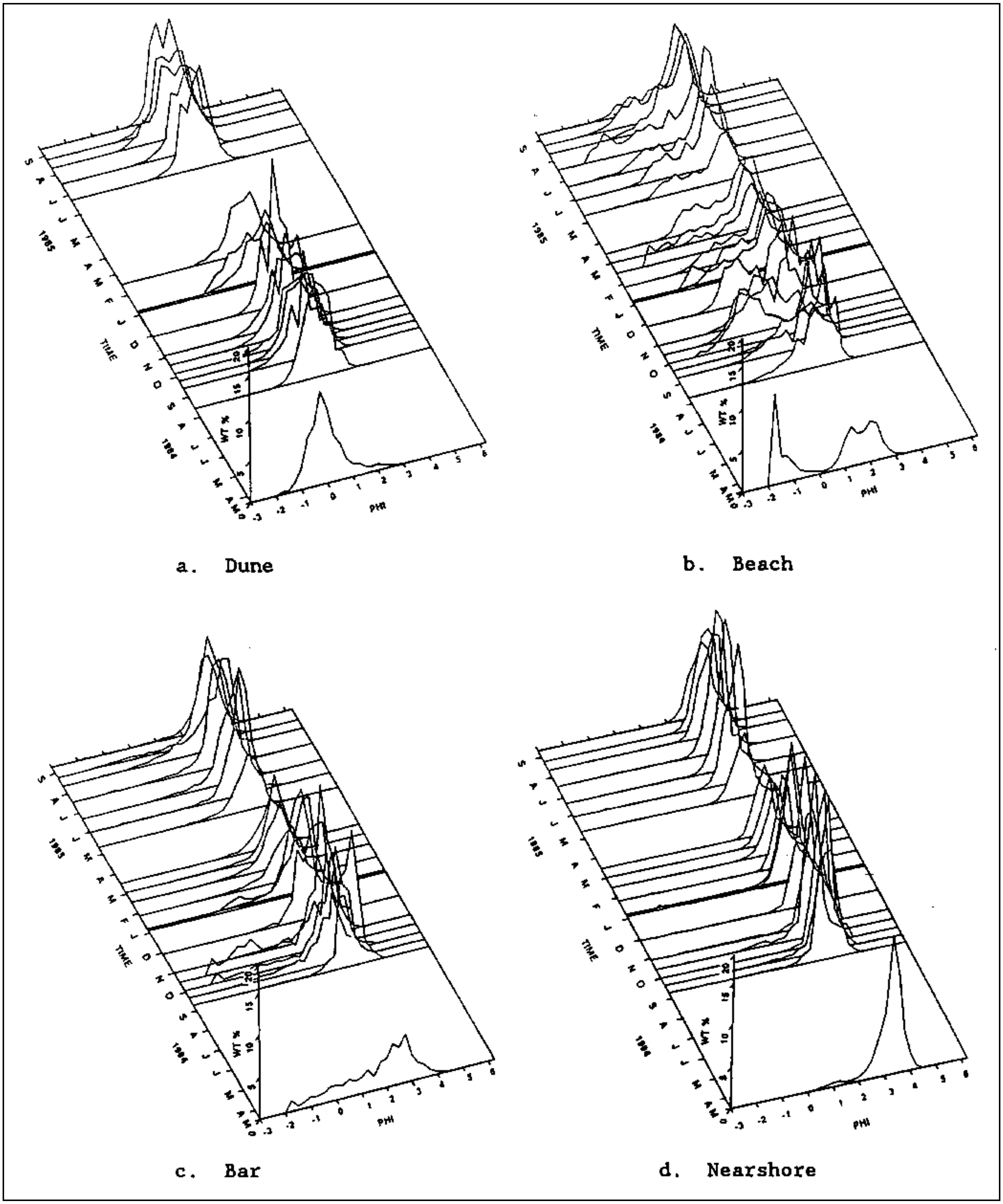

Figure 2-11. Composite grain size distribution curves for different geomorphic features along the profile, representing variations of composite grain size through time

From this list, it is obvious that accurate estimates of design waves are imperative in the proper design of a beach fill project. Wave characteristics for a beach fill design are determined by first estimating offshore wave statistics, i.e. in deep water or at a location of known water depth such as 30 or 60 m (100 or 200 ft). Offshore wave conditions are then used to formulate local wave statistics by accounting for appropriate transformation processes between the offshore location and project site.

(1) Wind data. Waves are generated as a result of local and far-field winds. Each project will have a different requirement because offshore fetches and exposures will vary. Therefore, good information about winds is required for accurate determination of wave statistics. Wind data, often in analyzed form, are available from several Federal agencies, such as the National Climatic Center and the National Weather Service, and many local government agencies. These local wind data are used to develop wind roses and other graphic descriptions of wind statistics that can be readily applied to the calculation of wave climate in areas where fetches are relatively short. Wind data are also important in assessing the importance of aeolian sand transport, which is described in a later section. The *Shore Protection Manual* and EM 1110-2-1502 provide detailed descriptions of the proper treatment of wind data for use in generating wave data.

(2) Wave statistics for beach fill design. Wave statistics should be determined at the project site to the best level of detail possible. These statistics are normally summarized as a probability distribution of wave heights and wave periods for each increment of compass direction. Most beach profile evolution models require that waves be specified just offshore of the project location in a water depth considered to be the depth of effective motion. The depth of effective motion is the offshore limit of beach profile adjustment and depends upon the time scale of interest (design-level storm). Hallermeier (1977) suggests that the annual depth of effective sand motion is approximately equal to twice the significant wave height, which is exceeded 12 hr per year. The distribution of wave heights and periods will include both typical and extreme values, and will indicate the direction from which these values impact the project site.

(3) Wave time series for beach fill design. As described later in this manual, most rigorous methods used for the design and evaluation of potential beach fill performance, i.e. shoreline evolution models, will require time series of storm waves. These data can be obtained from storm hindcasts using numerical wave models, or synthesized from a combination of local wave measurements and known meteorological information.

(4) Methods for determining design wave data. The method chosen to determine wave information for beach fill design will depend upon the magnitude of the project, characteristics of the fetch and surrounding shoreline areas, availability of data, and tools available for calculating wave characteristics. Details concerning methods for determining design wave data are presented in EM 1110-2-1414. For small projects or sites with limited fetches, simplified methods for wind and wave estimation should be used, such as those described in the *Shore Protection Manual* and in the ACES Manual (Leenknecht et al. 1990). For larger projects and those with complex wave generation mechanisms, e.g. open coast areas, the U.S. Army Corps of Engineers Wave Information Study (WIS) has developed offshore, and in some cases nearshore, wave statistics for Atlantic, Gulf of Mexico, Pacific, and Great Lakes coastlines. These types of wave data are also available for extreme storm conditions. WIS wave data can serve as a basis for developing design information at the local project site. WIS data can also provide long-term time series of wave conditions that can be directly used as input to shoreline evolution models. In areas where offshore wave information is not available, such data needs to be developed based on wind statistics for the area of interest and deepwater wave modeling. Such data should be developed by first hindcasting offshore wind conditions (both individual storms and long-term day-to-day conditions) which would then drive offshore and nearshore wave models to determine the wave conditions near the site of interest.

(a) Local design wave statistics are determined by transforming offshore wave conditions to a nearshore location adjacent to the project site. Wave refraction, shoaling, diffraction, and other relevant shallow-water processes must be considered. EM 1110-2-1414 describes the proper methods to perform these calculations. For small projects simplified methods are available in computerized form in the ACES Manual (Leenknecht et al. 1990). For large projects meriting more detailed wave information, such as areas where the offshore bathymetry and shoreline geometry are complex, or where coastal structures are present, shallow-water wave computer models should be used to generate nearshore design wave data from wind input or to transform offshore wave data to the project site. The Coastal Modeling System (Cialone 1991), provides details of a number of nearshore water wave models applicable to this situation.

(b) As mentioned earlier, rigorous techniques for designing and evaluating beach fills require time series of wave conditions. A hindcast of wave conditions during historic storms, verified by local measurements, is desirable to evaluate the ability of a beach fill design to withstand short-term extreme events. A longer time series of wave conditions spanning several years, if available, can be used to assess the long-term evolution of a project. Important variables include the time series of wave height, wave period, wave direction, and wave spectra. Coincident coastal wind speed and direction are also important. If the project length is appreciable, or if the shoreline/offshore characteristics vary along the beach, wave hindcast model results should resolve the variations in wave conditions across the project shoreline.

b. Currents. Various types of nearshore currents can affect the potential success of a beach fill project. Currents can mobilize sediment and keep material in suspension. There are many documented types of currents that exist in the nearshore region; however, this section will only outline those currents that have been found to be instrumental in the mobilization and movement of sediment. The beach fill design process should include an assessment of the range of possible currents present in the project area and the potential for these currents to impact the stability of the fill material. Extreme currents in the longshore direction may redistribute the fill material in the downdrift direction and eventually carry the sediment out of the project area. Appropriate containment measures within the project area and at the project boundaries should be evaluated and designed in conjunction with beach fills if the potential for transport by currents is excessive.

(1) Longshore currents. Longshore currents are generated by the longshore components of wave motion that obliquely approach the shoreline. These currents flow parallel to the coastline at velocities that typically average about 0.3 m/sec (1 ft/sec) (Figure 2-12). The *Shore Protection Manual* (1984) presents an equation for the longshore current velocity as follows:

$$v = 20.7 \; m \; (gH_b)^{1/2} \; \sin(2a_b) \qquad (2\text{-}2)$$

where

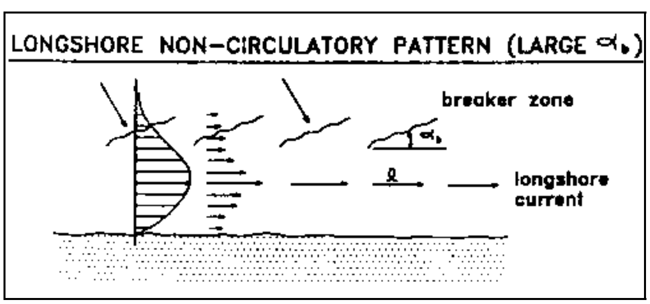

Figure 2-12. Longshore currents generated by the longshore component of wave motion obliquely approaching the shoreline

m = beach slope (meters (feet))
g = acceleration due to gravity (m/sec^2 (ft/sec^2))
H_b = breaker height (meters (feet))
a_b = angle between breaker crest and shoreline (degrees (radians))

(2) Ambient currents. Other types of currents should be evaluated and quantified for later assessment as to their potential for transporting sediment. These sources of current include:

(a) Rip currents. Concentrated jets that carry water seaward through the breaker zone acting to transport materials in the cross-shore direction. Most prominent when long, high waves produce wave setup on the beaches. An example of rip currents can be seen in Figure 2-13.

(b) River currents. The primary source of data and statistics is the United States Geological Service, which monitors river and stream flows regularly throughout the country.

(c) Tidal currents. The propagation of tides through coastal areas induces water surface gradients and currents. As part of its tide prediction service, NOS publishes tidal current forecasts and statistics for U.S. coastlines.

(d) Wind-driven currents. Wind stresses, especially during storms, induce currents in the water column. Information on the magnitude and direction of these currents is described in the next section.

c. Water level fluctuations. The recession of beach fills is most sensitive to the range of water levels that occur at the project site. Higher water levels allow erosive forces to act upon sediments located at higher elevations on the beach, allowing beach recession to proceed inland. The ultimate success of a beach fill in reducing storm erosion and flood damages is more dependent upon consideration of extreme water levels than any other parameter. Water level fluctuations that are considered in beach fill design include astronomical tides, wave setup, storm surges, and regional/ climatic effects. All of these types of fluctuations have different periods; however, many can occur simultaneously resulting in extremely high water levels. Methods for determining water levels are summarized in EM 1110-2-1414 and EM 1110-2-1412.

(1) Astronomical tides. Tides are periodic rising and falling of sea level caused by the gravitation attraction of the planets acting on the earth. Tide ranges tend to be higher during full moon periods, and are called spring tides. Detailed data concerning tide ranges are published annually in tide tables by the U.S. Department of Commerce, NOS.

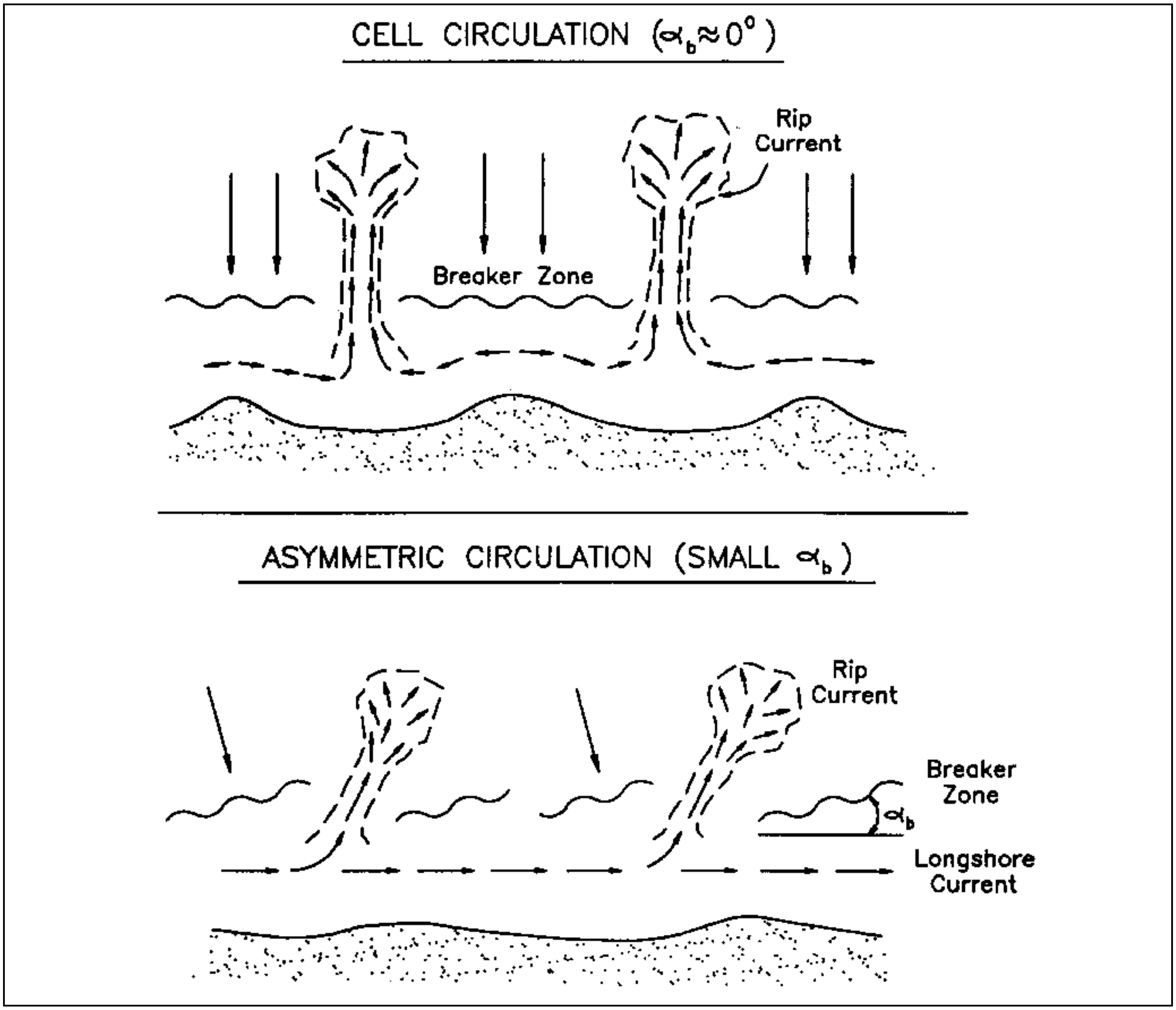

Figure 2-13. (a) Nearshore circulation cells with well-developed rip currents when breaker angles are near zero. (b) Asymmetric rip currents when breaker angles are small

Tide ranges vary between 23 ft in northern Maine to 2 ft on the Atlantic Coast of Florida, 1 ft to 2 ft on the Gulf of Mexico, and 5 ft in Southern California to 15 ft in the State of Washington. Tidal ranges vary with the wide variety of coastal landforms (Hayes 1980) and are characterized as microtidal, mesotidal, and macrotidal. Microtidal ranges occur on open ocean coasts while macrotidal ranges typically occur where the tide is dissipated across wide sloping areas or confined to estuaries or gulfs. Mesotidal ranges occur where both microtidal and macrotidal features are found. Figure 2-14 illustrates tidal types and ranges for various coastal landforms. Statistics of tidal data and a discussion of tide predictions and datums is presented in "Tides and Tidal Datums in the United States" (Harris 1981) and software applications can be found in the ACES Manual (Leenknecht et al. 1990).

(2) Wave setup. Wave action will cause a super elevation of the mean water level along the coastline called wave setup. Wave setup can be appreciable during storms, with theoretical magnitudes between 15 percent and 30 percent of the breaking wave height. The *Shore Protection Manual* (1984) and EM 1110-2-1414 present a method for calculating the wave setup if wave conditions and beach slope are known.

(3) Storm surges. A wind blowing over a body of water exerts a stress on the water surface which in turn induces a

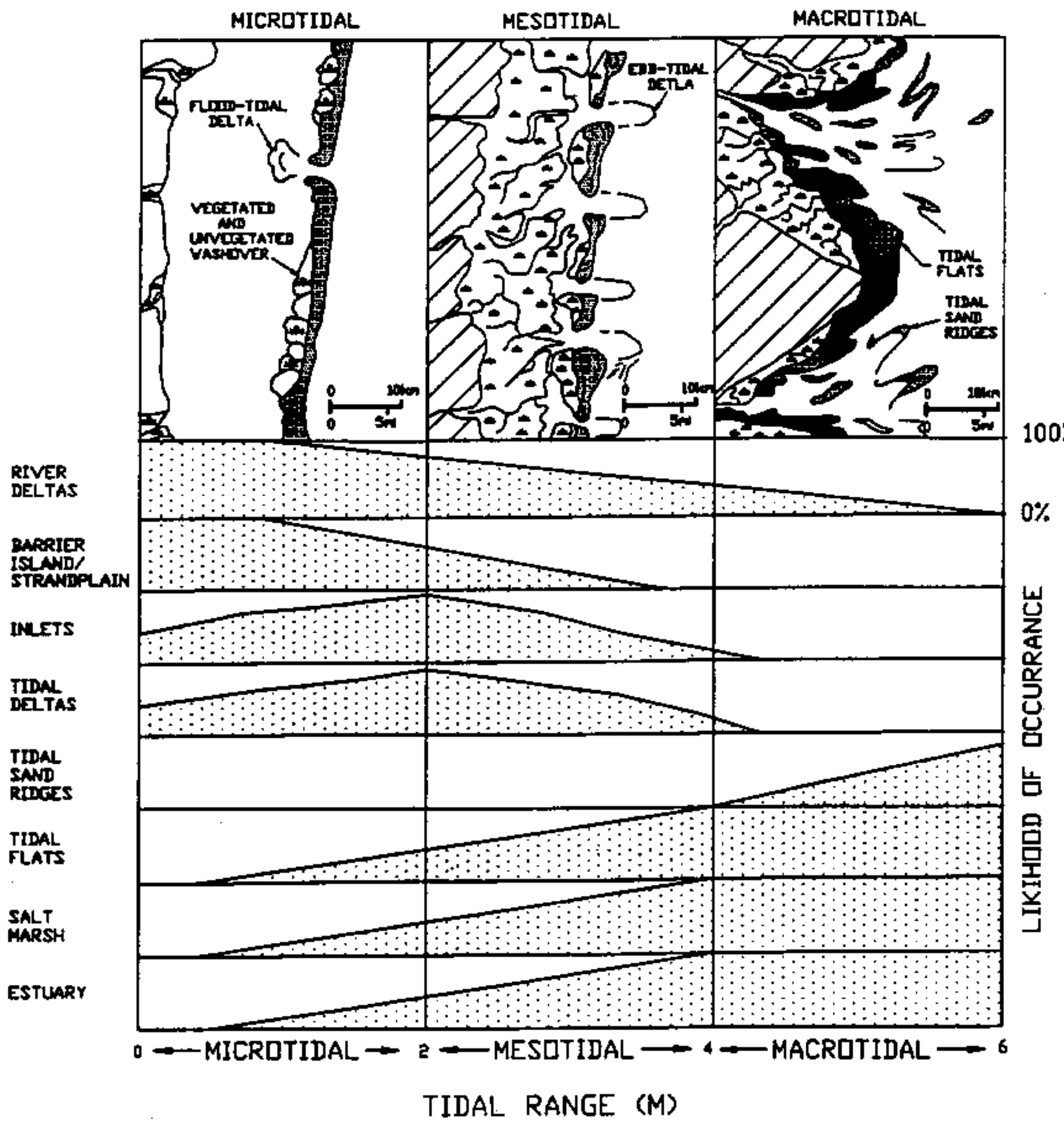

Figure 2-14. Macroscale morphology of microtidal, mesotidal, and macrotidal coastlines (modified from Hayes (1980))

surface current in the general direction of the wind. These horizontal currents are impeded in shallow-water areas causing a rise in water level. The storm surge is the departure from the normal water level due to this process and the variations in atmospheric pressure. The severest of storms may produce surges in excess of 8 m (26 ft). Elevation and duration of storm surge are dependent upon a number of factors: wind velocity, storm barometric pressure, storm translation speed, latitude, and other effects. Storm surge statistics have been developed for most coastlines by the National Oceanic and Atmospheric Administration, are provided in the form of storm-induced water level as a function of storm return period, and can be found in EM 1110-2-1412.

(a) More rigorous approaches to beach fill design and evaluation require the availability of storm time series of water levels. Gauge data are available for some locations and for some isolated events; however, gauge measurements are generally inadequate for providing a complete set of water level data. A storm surge numerical model, calibrated against available local water level gauge data, is the best tool available for predicting storm surge. Such a model can simulate all of the complex processes throughout the entire duration of the storm. A complete set of extreme storms can be simulated, providing time series of water levels for use in beach response models if a good statistical base for the determination of design water level elevations is available. Details related to the implementation of such a model can be found in EM 1110-2-1412.

(4) Regional/climatic factors. Coastal areas such as those on the Great Lakes are subject to seasonal and annual changes in water level caused by hydrologic and regulatory control works (dams). In the Great Lakes areas water levels peak during summer and fall to their lowest levels in winter, primarily due to runoff which begins during the spring thaw. Longer term variations in Great Lakes water levels are due to long-term variations in average annual precipitation levels. The maximum difference between the peak water level and the lowest water level observed on the Great Lakes during the period 1900 - 1977 is about 2 m (6 ft). It is recommended that gauge data and statistical analyses of available data be reviewed to determine the importance of these factors in the beach fill design water level.

(5) Sea level rise. An often-ignored component of the design water level at a coastal beach fill site is the long-term rise in sea level. At a beach fill site, this global (eustatic) sea level rise information should be combined with information about coastal shelf sinking rates, plans for local regrading, and other local processes that will determine long-term relative changes in sea level. Using this information, the gradual changes in sea level can be incorporated into the beach fill design and the requirements for long-term renourishment. Historical shoreline change information, which is used as a basis for determining renourishment requirements, includes the effects of past sea level changes. When estimating nourishment requirements for rates of sea level rise different from the historical rate, only the incremental increase in shoreline response due to the incremental difference in projected rate of sea level rise needs to be added to the nourishment requirement.

d. Selection of design conditions. Fills for storm and flood protection will generally be designed for severe storm events and their performance evaluated over a range of storm events with surge elevations up to a 0.02 average annual exceedance frequency event. Storm parameters such as surge elevation and wave height and duration of the storm event, should be delineated for events used to identify the optimum protection.

(1) Average conditions. Average wave, current, and water level values determined for the beach fill site should be used to determine the most probable beach profile and planform condition during various seasons. Long-term average wave conditions should be used to estimate longshore transport rates, which will govern the long-term performance of the fill. The GENEralized model for SImulating Shoreline change (GENESIS) described by Hanson and Kraus (1989) is a PC-based program that can be used for estimating long-term longshore transport rates over beach lengths of 1 to 200 km (1 to 125 miles). This program is discussed in greater detail in Section 4-2.

(2) Short-term variability. It must be recognized that wave, current, and water level conditions vary considerably from year to year, season to season, and even day to day at every coastal site. The variation (standard deviation of average wave heights, for instance) of average annual and seasonal records from year to year can be calculated.

(3) Extreme events. Storm conditions will normally result in the most severe design constraints. Design storm events must be developed through an analysis of the entire population of important historical storms that have impacted the area. In the northern Atlantic, northeasters are most prevalent, whereas in the southern United States, hurricanes are most prevalent. The mid-Atlantic states experience a mix of both northeasters and hurricanes, both of which can be extremely severe. As large a population of storms as possible should be examined and preferably hindcast to accurately determine the design level criteria. It should also be recognized that at every design level, there is a risk that more severe storms will impact the area and the implications of such an occurrence must be evaluated. Besides the peak storm parameters such as water level, wave height, period, and direction, the duration of extreme waves, currents, and water levels also determines the recession of beach fills. Along with stage frequency, a shoreline recession frequency will be needed to evaluate the beach fill design.

(4) Long-term variability. As discussed above, certain design parameters will exhibit long-term variability. As an example, seasonal/climatic effects produce pronounced changes in water levels on the Great Lakes. Weather patterns exhibit long-term cycles in temperatures and storm conditions. Such variabilities can be incorporated into the development of design criteria by examining historical data over as long a period as possible, preferably much greater in length than the desired life of the project. Larger storm protection and flood control projects often include reviews of data collected over 50 to 100 years of record. Analyzing data over these long time periods will average out the short-term variability. Short records of design conditions may be biased by both the statistically incomplete record and long-term environmental cycles.

2-6. Coastal Processes

The action of winds, waves, and currents in the coastal zone is constantly occurring and changing. These forces transport beach material in the onshore/offshore direction and along the coast. The design of a beach fill project will account for the range of possible nearshore processes.

a. Nearshore wave transformation. As waves travel into shallow water, they undergo transformations, altering the wave height, length, and direction. This effect begins at a water depth that is approximately one half the deepwater wave length and becomes significant at one fourth the deep-water wave length. Important processes include wave shoaling, breaking, refraction, diffraction, and generation by nearshore winds. The proper treatment of these effects is described in EM 1110-2-1414. Recent developments in numerical computer models have automated the calculations and improved their accuracy. The resulting nearshore wave conditions just offshore of the beach fill site should include wave statistics and time series of the significant wave height, wave period, root mean square (RMS) wave height, and mean wave direction.

b. Runup and overtopping. After propagating through shallow water and breaking through the surf zone, waves encounter the beach and run up the beach face. The ultimate elevation of wave runup is determined by the beach slope and roughness, wave characteristics, and sediment characteristics. If the purpose of a beach fill project is storm and flood protection, the ultimate configuration of the beach fill should be designed to minimize the occurrence of waves overtopping the beach and subsequently flooding inland areas. It should be noted that a selected design will not prevent all damages and will generally result in a certain level of residual damages which cannot be economically eliminated. Runup and overtopping are described in greater detail in Section 4-3.

c. Sediment transport processes. Littoral transport is the movement of coastal sediment in the onshore/offshore direction (perpendicular to the shoreline) and the longshore direction (parallel to the shoreline). In the surf zone, water velocities and eddies beneath breaking waves bring sediment into suspension. Average nearshore current velocities determine the net direction and rate at which sediment is transported.

(1) Onshore/offshore transport. Any location on a beach can be viewed as a profile in the onshore/offshore direction. This two-dimensional representation at a given location along the beach is termed a "beach profile." The beach is an effective mechanism which causes waves to break and dissipate their energy. It is a buffer between the ocean and the coastal property. The beach profile must maintain its material in order to provide protection to inland areas. Material moves between the beach face and the surf zone as wave and water level conditions change. Various theories exist to describe such movement, which have been put into use through empirical and numerical models. This section describes the phenomenon of onshore/offshore transport; Section 4-2 describes the theories that attempt to simulate the transport phenomenon.

(a) Mild (or summer) beach profiles in general exhibit a wide upper beach or berm, and a smooth monotonic offshore profile with no bars. The wave climate corresponding to such a condition is also mild and water level variations are usually only due to astronomical tides.

(b) Storm (or winter) beach profiles typically have a narrower upper beach or berm and a series of bars through the surf zone. Higher water levels during winter conditions bring wave energy higher up on the beach, carrying the beach berm material out to offshore bars.

(c) The volume of sand in the summer and winter profiles at a given beach location will be essentially constant; however, extreme events may cause a net loss from the area by carrying sediment to offshore locations where it cannot be recovered in less severe conditions. In addition, longshore transport may remove material from the system by carrying sediment to neighboring beach areas.

(d) The concept of "equilibrium profile" is used extensively in the analysis of the response of a beach to long-term or extreme wave conditions. Based on long-term measurements of beach profiles, it has been found that a given profile will tend to maintain a generally consistent shape as long as the beach sediment size and long-term wave climate remain constant. The seasonal variations in profile shape discussed above are considered short-term perturbations to the long-term equilibrium profile. The overall equilibrium profile shape has been found to be governed primarily by sediment size characteristics (Dean 1991). Based on studies of beaches in many environments, Bruun (1954) and Dean (1976, 1977) have shown that many ocean beach profiles exhibit a concave shape such that the depth varies as the two thirds power of distance offshore along the submerged portions as defined by:

$$h(x) = Ax^{2/3} \tag{2-3}$$

where

h = water depth at distance x from the shoreline (meters (feet))

x = distance from shore (meters (feet))

A = a scale parameter which depends mainly on sediment characteristics (meters$^{1/3}$ (feet$^{1/3}$))

This surprisingly simple expression asserts, in effect, that beach profile shape can be calculated from sediment characteristics (particle size or fall velocity) alone. Moore (1982) graphically related the parameter A, sometimes called the *profile shape parameter*, to the median grain size d_{50} (Figure 2-15). Dean (1987) related the parameter A to the sediment fall velocity *(w)*. On a log-log plot, the relationship was almost linear and could be expressed as:

$$A = 0.067 w^{0.44} \tag{2-4}$$

Hallermeier (1981) developed fall velocity equations for a wide range of beach conditions expressed as:

$$w = 14 D^{1.1} \tag{2-5}$$

where w is the fall velocity (cm/sec) and D is the mean sediment diameter (mm). A fall velocity based on Equation 2-5 assumes common beach sand with diameters ranging from 0.15 mm to 0.85 mm, water temperatures ranging from 15 to 25 °C, and fresh or salt water.

(2) Longshore transport. Waves breaking at oblique angles to the shoreline generate currents which transport

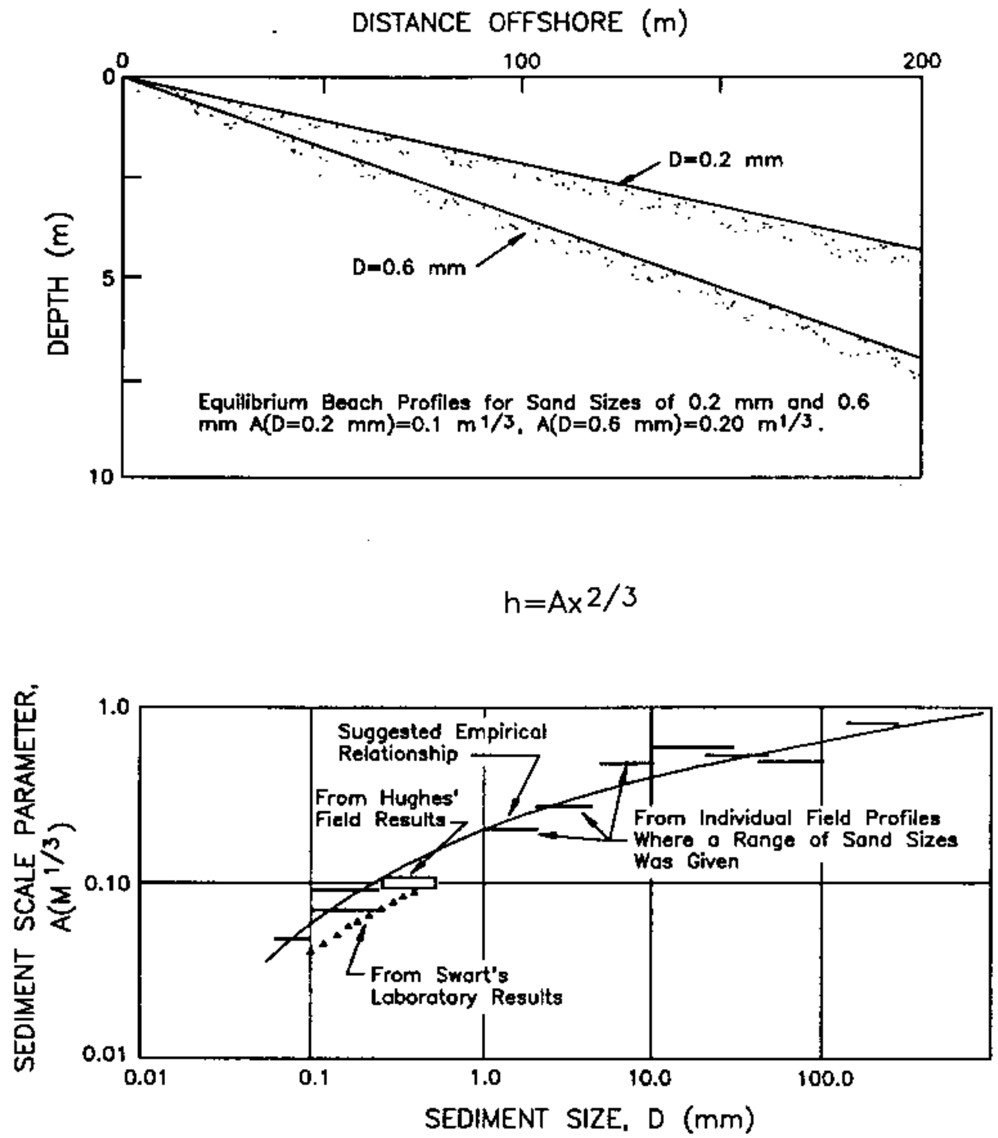

Figure 2-15. Beach profile factor *A* versus sediment diameter *D* in the relationship $h = Ax^{2/3}$ (modified from Moore (1982))

sediment in the longshore direction. Most of this transport occurs within the surf zone. Material is placed in suspension by turbulence generated by breaking waves, and the suspended material is then carried downdrift by the longshore current. Sediment movement also occurs along the bed in areas where wave-induced velocities are appreciable. Over extended periods of time, waves will approach the beach from a wide range of directions causing longshore transport in both directions along the beach as previously shown in Figure 2-9. The total annual amount of transported material is termed the gross transport rate and the difference between the annual amount of material transported in each direction is called the net transport rate. Note that the instantaneous transport rate can be extremely variable and much higher or lower than the annual rates. Estimates of longshore transport rates can be made in a number of ways. A combination of the approaches will provide the best estimate of the transport rates and the variability associated with the estimate.

(a) If transport rates have been determined for nearby coastal sites with similar conditions and exposures using one of the methods listed below, that rate can be adapted with modifications based upon local conditions. Care must be taken when adapting rates from other areas because longshore transport rates are very sensitive to wave angle, which is governed by the local orientation of the shoreline, and sediment size, which can vary from beach to beach.

(b) Sediment traps along the coastline can be monitored or reviewed via aerial photos to determine the amount of accumulated material nearby. Traps might be headlands, spits, groins, or surface outfalls. The location of the accumulation can indicate the net direction of movement as previously shown in Figure 2-3. Volumes can be obtained by assuming a constant beach profile over time or by surveys taken prior to and after accumulation.

(c) Commonly accepted formulae for calculating transport rates based upon wave characteristics at the breaker line are given in EM 1110-2-1502 and Chapter 4, Section V-3 of the *Shore Protection Manual* (1984). Longshore transport rates will indicate how rapidly a beach fill will be carried along the coastline and possibly out of the project area. They will also indicate whether any containment structures might be required to maintain a stable beach fill and if the beach fill will impact neighboring areas.

(3) Overwash. Extreme storm activity often generates high waves and storm surges that flood coastal areas. The incoming flood waters overwash low-lying land, carrying a high concentration of sediment which moves across the beach. The sediment eventually drops from the flood waters, leaving what is called overwash deposits. The amount of sediment carried and deposited during such events can only be estimated based on historic data, if at all. Beach fill projects can aid in raising coastal land elevations, thus inhibiting overwash.

(4) Aeolian transport. Large volumes of sand can be transported from the beach face and backshore by wind. On oceanfront coastlines, onshore wind transport rates can be as high as 7.5 m^3/m (10 yd^3/ft) of material per year. Sediment carried into an area by longshore transport or onshore transport can be carried inland by onshore winds, which carry the sand into the backshore area and, in some cases, out of the beach area. Wind velocities required for transport of sand will vary with the sediment size distribution on the beach, wind profile, beach slope, presence of vegetation and fences, and other minor effects. Knowledge of the aeolian transport rate in a given area will indicate the possible fate of a portion of the water-borne sediment and the potential accretion rates in foredune systems.

2-7. Sediment Budget

A sediment budget is a summation of the amount of sediment in a given period of time that is transported into or out of a designated area. Sediment budget studies of the project area and closely adjacent areas are an important element of beach fill design data because they indicate the amount of erosion or accretion occurring in a designated area due to ongoing natural processes and provide a means of estimating the magnitude of longshore transport. From this data, the initial and periodic maintenance fill volumes needed to meet project requirements can be estimated as shown by EM 1110-2-1502. The principal method of a sediment budget study is to determine the amount of sediment being added to the study area by sediment sources and the amount being lost to sediment sinks. In the context of sediment budget studies, a source is any process or feature contributing sediment to the area as, for example, erosion of a cliff behind the beach or stream discharge. A sink is any process or feature that decreases the amount of sediment in the study as, for example, a submarine canyon or inlet.

a. Cross-shore transport. In common with fluvial features, the movement of sediment perpendicular to the beach can constitute either a source or a sink. In general, it is thought that most movements of this kind occur primarily in the littoral zone which would normally be well within the boundaries established for the sediment budget calculations, and thus would not involve net gain or loss of sediment. However, several sources recently reviewed by Williams and Meisburger (1987) have reported indications of onshore transport from the continental shelf in places. In some studies evidence of onshore transport from the continental shelf was derived from natural tracers or other indicators that did not provide data on the amount of material involved. In others, however, the evidence was based on sediment budget analyses showing that some sediment reaching the study area probably could not have come from sources other than the inner shelf. The amount of sediment assumed to be shelf-derived in these studies was a significant part of the total sediment supply.

(1) Landward transport of sediment can also act as a sink where storm overwash carries material from the beach beyond the normal inland boundary. These washover features may impound sizable amounts of sand outside the reach of direct marine processes; however, on retreating barrier islands, it may be recycled into the beach deposits at some future date.

(2) Offshore transport of sediment beyond the closure depth may be a significant sink in many places but has not been widely documented. This is probably due more to the expense of obtaining the field data necessary to trace offshore movement than rarity of its occurrence. One way of obtaining information about offshore transport is to account for the losses to other known sinks such as overwash and littoral transport and assume that the difference between total input and known losses represents offshore transport.

b. Longshore drift. Frequently the largest volume of sediment moving in a study area is transported by the littoral drift system which moves material alongshore.

(1) Littoral drift acts as both a source and a sink for littoral material within a given segment of shore. If no obstructions to littoral movement exist in the area to retain sediment and the wave angle and height remain constant along the reach, any gains of material from updrift sources may be balanced by equivalent losses across the downdrift boundary. It is often the case, however, that some of the material is trapped by updrift headlands, inlets, or coastal structures and the loss of material across the downdrift boundary is greater than the input, resulting in a net decrease of sediment volume. In some instances, the input of sediment from all sources is greater than the losses and there is a net increase in volume. However, this additional material may be concentrated in a small area, for example, inlet-associated shoals, so that a deficiency exists for most of the study area.

(2) The movement of littoral material in a shore-parallel direction is called longshore transport. The rate of longshore transport is expressed as the volume of material moving past a fixed point during a given period of time. The movement can be either to the right or left of an observer looking seaward from the fixed reference point. The gross longshore transport rate Q_g is the sum of the material moving both to the right Q_{rt} and left Q_{lt} of the observer. Thus,

$$Q_g = Q_{rt} + Q_{lt} \tag{2-6}$$

The net longshore transport rate Q_n is an expression of the difference in the rate of movement to the right and left of the observer. Thus, longshore transport rates can be estimated by a number of different methods (see EM 1110-2-1502).

c. Aeolian processes. Wind can act as both a source and sink of beach and dune sediment. Wind is usually a sink for beach sediment which is picked up from the dry backshore area and carried inland or out to sea. On dune-backed coasts, windblown sand from the dry beach backshore area is the most important source of the dune sediments. Unless well stabilized, however, dunes can also lose large amounts of sand by wind deflation. In making quantitative evaluations of aeolian influence, it is difficult to discriminate between wind and wave effects on the beach and frontal dunes. Estimates of transport volumes can be made by using sand traps to intercept windborne sediment coupled with frequent measurements of wind velocity and direction. Changes in dune topography depicted on sequential maps or aerial photographs over specific time intervals can also be used to calculate losses of dune sediment; however, dune fields are often so complex that calculating overall losses or gains requires a large amount of detailed data and frequent surveys. In most cases, evaluation of gains or losses can be limited to the frontal dunes which are the most significant in terms of shore protection.

d. Organic production. Almost all beaches contain some material composed of the skeletal hard parts of marine flora and fauna living in the beach and nearshore areas. Mollusks are the chief contributors in most places, but a number of other organisms also add material.

(1) Organically produced (biogenic) particles in beach sediments may have been produced locally or have been transported from other areas. Some biogenic particles such as echinoid fragments and some calcareous algae are delicate and probably survive only a short time in the turbulent beach environment. In addition, some organic material is so easily transported that it seldom accumulates on the beach but moves to deeper water offshore where it is more stable.

(2) In general, on the coasts of the United States,

biogenic contributions to beach sediment are relatively small in most places; however, locally, where detrital sediment supply is low, organic production is relatively high, or fossil shell material is being uncovered, the biogenic contribution can be significant.

(3) Since the skeletal fragments found in beach deposits are nearly all composed of calcium carbonate, the approximate weight percentage of biogenic material can be determined by an acid digestion test of representative sub-samples.

(4) Because calcium carbonate particles are not as hard as quartz and other inorganic minerals in beach deposits, they are abraded at a faster rate. Although shell fragments in beach deposits often have rounded edges and a polished surface due to abrasion, little is known about the time needed to abrade the particles until they are too small to be retained on the beach and move offshore.

e. Tidal inlets. Tidal inlets may at times be sources of sediment derived from estuaries or back-barrier deposits but for the most part, these sediments are too fine to persist in the littoral zone and are transported offshore. By far, the main effect of tidal inlets is as sediment sinks which trap or deflect material moving in the littoral stream as previously illustrated in Figure 2-6. The exception is a beach on the downdrift side of a tidal inlet which may receive a significant percentage of its sand supply by inlet bypassing processes.

(1) Much of the material trapped by inlets is deposited in ebb, flood, and mid-channel (middle ground) shoals in the immediate vicinity of the inlet. Where tidal currents are strong, some of the littoral material may be carried seaward by the ebb current to be deposited in offshore areas.

(2) Tidal inlets can influence the sediment budget for shore areas a considerable distance downdrift of the inlet itself. For this reason, inlets updrift of the project boundaries should be considered in an analysis of sediment gain or loss in the project area.

(3) Estimates of the amount of sediment from the longshore drift trapped at inlets can be made by comparative analysis of sequential maps, charts, and aerial photography documenting the growth of inlet-associated shoals and dredging records of the inlet channel.

f. Submarine canyons. Submarine canyons are prominent features incised in the continental shelf and the slope bordering coastal areas. Where these features approach the shore they become effective traps for littoral and nearshore sediments moving in an alongshore direction. Once trapped in the canyon, the material progressively moves seaward into deep water and is permanently lost.

2-8. Existing Structures

Since beach fill operations are often undertaken to restore eroding beaches, they may contain hard structures that have been previously constructed in an attempt to stabilize the beach and protect inland areas. In some cases, it may be desirable to remove the structures prior to the fill operation to restore more natural conditions and enhance recreational and environmental quality. In other cases, the structures may be retained to retard loss of fill material or provide continued protection to inland areas. In order to make decisions on the disposition of structures and evaluate their function on the postfill beach, an inventory of existing hard structures should be a part of the site characterization study. The inventory should include information on the location, type, condition, and effectiveness of existing structures and their probable function on the beach after project completion. If possible, the original design data for the structures should be obtained for basic information and comparison with current conditions.

a. Location and dimensions. The location of each coastal structure in the project area should be determined and plotted on large-scale maps or identified on aerial photographs. Major dimensions should be obtained from original design drawings, if available, or measured onsite.

b. Structure types and materials. There are several types of hard structures built in coastal areas to retard shore erosion, trap sand in the littoral stream, and protect inland areas against flood and wave damage. The most common types of these coastal structures are seawalls, revetments, bulkheads, groins, and breakwaters. Detailed examples and discussion of these structures can be found in EM 1110-2-1614, EM 1110-2-1617, EM 1110-2-2904, and the *Shore Protection Manual* (SPM) (1984).

(1) Seawalls are usually massive structures used to protect inland areas against floods and large storm waves. Revetments serve the same purpose but are of lighter construction and suited to withstand relatively low-energy waves. Bulkheads are used to retain fill and prevent collapse of cliff faces. Although designed to withstand outward forces, they are often erected in places exposed to wave attack and must be designed to withstand expected wave forces (see EM 1110-2-1614).

(2) Groins are low-wall-type structures sited perpendicular to the shoreline that are erected to trap and hold sand moving in the littoral stream. Offshore breakwaters have been used as beach erosion control structures as well as for

harbor protection. They are usually located in relatively shallow water and are often segmented to allow some of the wave energy to reach the shore and maintain longshore processes (see EM 1110-2-1617). Jetties, although primarily intended to stabilize and protect navigation channels, may have a pronounced effect on the adjacent shore areas and should be included in the inventory (see EM 1110-2-2904).

(3) The useful life of hard structures is partly determined by the materials from which they are constructed. The most common materials found in coastal structures are concrete, asphalt, stone, steel, and timber. Descriptions of coastal structures for the site characterization study should include information on the materials used for their construction and the form in which used, e.g., cast concrete, concrete rubble, concrete sheet piling.

c. Condition. In time, all coastal structures deteriorate. Their longevity as effective structures depends on their design, materials from which they are constructed, severity of the environment, and maintenance. Some structures may be severely damaged or destroyed during the course of a single storm while others survive intact for long periods of time. The condition of all coastal structures in the project area should be determined by thorough onsite inspection for any signs of damage or deterioration that render them less functional or increase vulnerability to damage by environmental forces.

d. Effectiveness. An important consideration in regard to existing coastal structures is how well they have fulfilled their design function. In many instances, coastal structures do not fully meet their purpose because of rapid deterioration or damage, inadequate design, or poor construction. In addition, some structures function adequately but create environmental problems that outweigh any benefits they produce, for example, a groin field that creates serious sediment deficiencies in downdrift areas. Evaluation of structure effectiveness is based on knowledge of its original purpose and past construction history. Valuable sources for this knowledge are the original design data, post-project monitoring reports, sequential aerial and ground photography, and recollection of local residents. Historical records of wave and water level fluctuations are also valuable in assessing the causes of structural damage.

e. Effects on project. Where coastal structures already exist in a project area, an evaluation should be made of whether or not they will have an adverse, neutral, or beneficial effect on the project. The analysis techniques and numerical models discussed in Chapter 4 of this report may be used in this evaluation.

(1) In cases where pre-existing structures have been damaged, have produced no beneficial effect, or have negative effects on the environment or recreation, it may be desirable to remove them prior to project construction.

(2) Structures that are functional and are expected to have a continued beneficial effect are best left in place unless environmental or aesthetic values should dictate otherwise.

(3) Of the structures that may be present in a project area, groins, jetties, and detached offshore breakwaters have the most direct effect on beach fill operations because they tend to retard losses of fill material. In evaluating these structures, it is desirable to obtain as much information as possible on their past performance in order to make a reasonable prediction of their performance before (without-project condition) and after the fill operation (with-project condition).